

ON THE HISTORY AND DEVELOPMENT OF THE THERMIONIC VALVE. BY SIR AMBROSE FLEMING, M.A., D.Sc., F.Inst.P., F.R.S.

REPORT OF A DISCOURSE GIVEN AT THE TWENTY-FOURTH
ANNUAL EXHIBITION OF THE PHYSICAL SOCIETY

IN its earliest form the thermionic valve was the first of a type of novel wave detectors, making use of the electron emission from incandescent solids in a vacuous space, in wireless telegraphy. Its initial invention arose from attention given to the physical problems presented by the incandescent electric lamp. For years various inventors had tried to solve the problem of devising a lamp of small candle-power suitable for domestic use which should produce light by the incandescence of some material heated electrically. The solution was reached by Sir Joseph Swan and Mr T. A. Edison who found it by enclosing a carbon filament made by carbonizing some organic fibre in an exhausted glass bulb. Swan made his first filament by carbonizing a cotton thread previously parchmented by sulphuric acid. Edison bent a strip of Japanese bamboo into a horse-shoe form and carbonized it by heating it in an iron box filled with powdered charcoal. In both cases it was then mounted in a glass bulb and leading-in wires of platinum sealed through the glass wall. Edison, moreover, worked out all the necessary details of switches, sockets, conductors, chandeliers and brackets for house use, and further the details for supply and distribution of electric current. The first carbon filament lamps gave light at the rate of 1 candle-power for 3.5 to 4 watts of electric power, and were therefore not impossible for practical use.

In the spring of 1882 I was appointed Scientific Advisor to the Edison Electric Light Company of London, whose first offices were at No. 57 Holborn Viaduct. This office and near-by buildings were electrically lit by Edison incandescent lamps supplied with current from Edison dynamos in the basement of No. 57.

These early carbon filament lamps soon became blackened, by the deposit of carbon evaporated from the filament, on the interior of the bulb. In certain cases when the filament had been overheated at one spot the carbon atoms seemed to be shot-off in straight lines, and the result was to leave a white line of no deposit on the glass where it had been shielded from bombardment by one leg of the carbon loop from projected carbon atoms from the other. This effect attracted my attention and I communicated two papers to the Physical Society on it, one in 1883 and a second in June 1885 in which I described the effect and called it a "molecular shadow."*

In 1883 Edison made an important experiment by sealing into the bulb of one of his carbon filament lamps a platinum wire carrying a metal plate placed between the legs of the carbon horse-shoe filament, and found that when a current meter was connected between the plate and one terminal of the carbon, which was rendered incandescent by a direct current, the ammeter showed a small current of a milliampere or so, passing when it was connected on one side to the positive terminal of the filament, but no current or nearly none when connected to the negative filament terminal. He put this observation on record but made no technical application of it nor gave any physical explanation of its nature†. Edison gave some lamps made with middle plates to the late Sir William Preece, who made some additional observations on this so-called "Edison Effect," but he also failed to give any

* *Proc. Phys. Soc.* 5 1883 (283). Also *ibid.* 7 1885 (178).

† *Engineering*, Dec. 12, 1884 (553), also U.S.A. Patent Specification No. 307,031 of Nov. 15th, 1883, of T. A. Edison.

explanation of its cause*. The subject then attracted my attention, and between 1884 and 1886 or 1887 I made a large number of observations on it which were described by me partly in a paper to the Royal Society in 1889 and more fully in a Friday evening Discourse at the Royal Institution, London, in February 1890, but most completely in a paper to the Physical Society on March 27th, 1896†. In this last paper I described effects which confirmed the observations of Edison and Preece, but I added two others of great interest. The first of these was that the so-called "Edison effect" is not only shown with carbon filament glow lamps as used at that date but is also exhibited when a platinum wire is heated to incandescence in a vacuum. The other, of more importance, was my observation that from all parts of a filament of carbon when heated to incandescence *in vacuo*, particles are being given off which carry a charge of negative electricity and these can discharge instantly a conductor which has a charge of positive electricity when it is connected to a metal plate in the bulb which is carried on a wire sealed through the glass. It must be remembered that at that date we had no knowledge of the existence of negative electrons.

That great discovery was not made until nearly ten years later by Sir J. J. Thomson. Hence I assumed erroneously then that the negative electric charges were carried by atoms or ions of carbon or metal. The experiments showed, however, that torrents of negative electricity were sent off from the brightly incandescent filament. They also proved (as noted previously by Hittorf) that an electric current under very low voltage, viz. a volt or two, can pass through a rarefied gas or vacuum space provided the negative electrode is incandescent. Hence also that such an evacuated tube with one electrode hot has a unilateral conductivity as noted previously by other observers. These scientific experiments and observations had no technical application at the time they were made.

In 1899 I became associated with the Marchese Marconi as an adviser of his Wireless Telegraph Company, and assisted him in the transformation of his physical laboratory apparatus for creating space electric waves of long-wave length into engineering plant suitable for sending wireless telegraphic signals across the Atlantic from Poldhu in Cornwall to Newfoundland. At that time the only practically useful method of detecting these wireless waves was some modification of the Branly-Lodge coherer. Marconi had given it a very useful form, but it was easily set out of order by atmospheric discharges or near-by electric sparks. A little later Marconi devised his magnetic detector but the latter was not able to operate any signal recording instrument, being used solely with the Bell telephone. I was anxious to obtain some device capable of working a mirror galvanometer or syphon recorder as in submarine cable telegraphy. To do this I knew we must "rectify" or convert into direct electric currents the feeble oscillations produced in the receiving aerial or connected circuits. My thoughts then turned to my above described experiments.

In October 1904 I had some carbon filament lamps made with a metal cylinder surrounding the filament, the cylinder being carried on an insulated wire sealed through the wall of the glass bulb. I then found that, when the carbon filament was made incandescent by a direct electric current, the space between the filament and cylinder possessed a unilateral conductivity and could rectify a high frequency electric oscillation or pass only those movements of electricity for which the incandescent filament was the cathode. I applied the method at once as a receiver in wireless telegraphy, and was able to employ a mirror galvanometer as a signal-making instrument or a Bell telephone receiver in the case of spark wireless telegraphy. The method was described in a British patent specification. It was also described in a paper to the Royal Society‡. Almost immediately after it was taken into practical use as a wireless wave detector by Marconi's Wireless Telegraph Company.

* W. H. Preece, *Proc. Roy. Soc.* **38** 1885 (219).

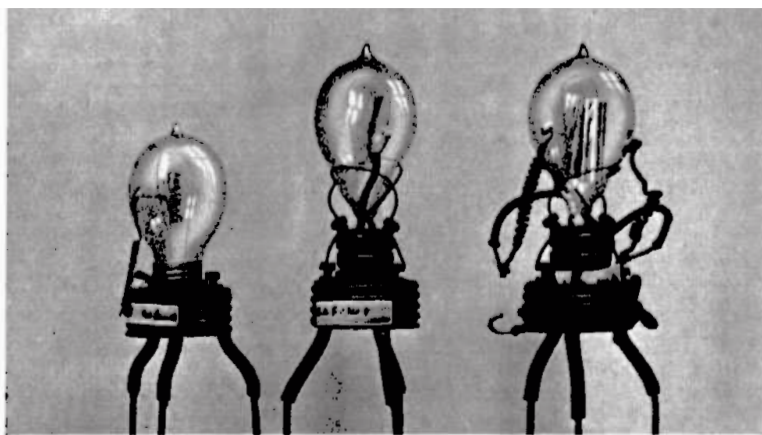
† *Proc. Roy. Soc.* **47** 1889 (118); *Phil. Mag.* **42** 1896 (52).

‡ *Proc. Roy. Soc.* **76** 1905 (476).

It should be noted that the crystal rectifier had not at that date been discovered. The first of these, viz. the carborundum rectifier, was only discovered by H. H. C. Dunwoody in the United States in 1906, or two years after my valve*, and the "Perikon" detector of G. W. Pickard a year later, in 1907.

I suggested the term "valve" for my thermionic rectifier because it is a simple intelligible English word of five letters implying means of allowing something, whether water, air, steam or electricity, to move in a circuit only in one direction, and it has been widely adopted. I regret to notice that many writers on radio-communication make use of the meaningless non-descriptive term "diode" in place of my word "valve". It has no advantage in brevity, and there is a distinct disadvantage in the use of a scientific gibberish which is not self-explanatory to the non-technical reader.

An important improvement was the introduction of the grid by Lee de Forest in 1907 to control the movement of the electrons from the hot cathode to the cold anode in the valve, thus making what is commonly called a three-electrode valve. I greatly blamed myself at the time for not foreseeing this simple method of electrostatic control of the electron current of my valve, thus converting a simple rectifying into an amplifying device. I was attempting an external control by a magnetic field, and although one of my original valves contained an anode formed of a zig-zag wire, I did not contain it in the same bulb as an anode plate.



Fleming's original rectifying valves, 1904

The three-electrode valve, or "triode" as some prefer to call it, has then four variable quantities which control the electron current in the valve, viz. (i) the anode or plate voltage v_p , (ii) the grid voltage v_g ; (iii) the filament temperature T , and (iv) the external impedance. No single formula can be given connecting the above quantities with the electron current i , but for a certain range in which the relations are linear we can express i as a function of v_g and v_p by the equation

$$i = av_g + bv_p.$$

The quantity a is called the "mutual conductance" and b is the valve "conductance," but this latter includes also the reciprocal of the impedance of the part of the plate circuit external to the valve. Broadly speaking, then, the action of the three-electrode valve is as follows: a battery of cells or some source of direct E.M.F. has its negative pole in connexion with the incandescent filament and its positive with the valve plate or anode with some impedance interposed. With a zero potential of the grid a certain electron current flows through the valve and a certain drop in potential takes place down the external impedance. If the grid is made negative the current and drop become less; and if positive become greater. The peculiar property of the triode is then that the change in the fall of potential down the external impedance in the plate circuit can be much greater than the change in grid potential which causes it. Hence the three-electrode valve can amplify potential and the amplification factor is the ratio of a/b as above defined.

The amplification is however kept small (i) by any capacity between filament and plate which reduces the impedance of the external anode circuit, and (ii) by any capacity between

* U.S.A. Patent Specification, 837,616 of 1906.

the grid and plate which reduces the mutual conductance or quantity μ of the valve, which is in other words the slope of the grid voltage characteristic curve at that point. This last defect, viz. grid-plate capacity, can be cured by introducing a second grid into the valve between the plate and control grid, which second grid is kept at a positive potential of about 60 to 80 volts above the filament. The result is to increase the amplifying power five to ten times. Such "screened grid" valves are now used in all good receiving sets. There are some other types of four-electrode valve to which reference, however, cannot be made in the space or time at disposal.

Another important improvement is the so-called "variable μ valve." The magnification power, denoted by μ , is determined partly by the closeness of the grid wires. In the "variable μ valve" the grid wires are spaced apart at gradually increasing distance from one end to the other. The magnification can therefore be varied or changed by suitably altering the negative bias or voltage put on the grid. In this way we can control within limits the response to electric waves and even make the control automatic.

Another noteworthy improvement is the "pentode valve." In a screened grid valve when the electron current is large the bombardment of the anode by the electrons liberates from the plate secondary electrons, and this creates a dip in the characteristic curve. This can be prevented by the insertion of a third grid between the anode and the screen grid, which is kept at the same potential as the filament by a connexion inside the bulb, making a pentode valve. Such pentode valve is useful as a final audio amplifying valve in receiving sets employing a loud speaker.

The developments in the material of the cathode or filament must next be passed in review. In the earliest valves carbon was the filament material, as in the case of incandescent lamps. In 1908 in a patent specification* I mentioned particularly the advantage of tungsten as material for the valve cathode. In or before 1914 Irving Langmuir in America drew attention to the greatly increased thermionic emission of tungsten when alloyed with thorium. The emission formula of Prof. O. W. Richardson is

$$I = A \sqrt{T} e^{-b/T},$$

where I is in amperes per square centimetre of surface, T is the absolute temperature of that surface and A and b are constants different for different materials. At the same temperature the thermionic emission from thorium is 1000 times greater than that from tungsten. Filaments of receiving valves are now made of thoriated tungsten and can be worked below visible red heat. They are called "dull-emitter" filaments.

Another type is the oxide-coated filament, due to the discovery of Wehnelt that the oxides of barium, strontium and calcium have great thermionic emission when heated. A platinum-iridium wire is coated with adherent deposits of barium and strontium and this is used as a cathode in valves very largely in the United States.

In the same British patent specification (No. 13,518) I described an alternative method of using my two-electrode valve as a detector of electric oscillations which is applicable also to the three-electrode valve and is now called "anode-bend" detection. If we plot a curve, the ordinates of which are the electron current of the valve and the abscissae the potential difference of the anode and cathode, we obtain the characteristic curve which has sudden changes in direction at two points called the bends. If we supply to the valve a steady voltage to bring the current just to the lower bend value, then the imposition of a high frequency oscillation at that point makes a sudden proportional increase in the current which can be detected by suitable arrangements and thus enables us to "rectify" an alternating current.

A fundamental quality of the three-electrode or grid valve is that it can generate as well as detect or amplify electric oscillations. If the anode circuit of the valve connecting anode

* Patent specification, No. 13,518 of June 25th, 1908.

and filament has in it an electromotive force, and is connected inductively with the grid circuit connecting filament and grid in one direction, these two currents reinforce each other, and electric oscillations are produced in both circuits, the energy required to maintain them being drawn from the battery in the anode circuit. In valves made for generating electric oscillations called transmitting valves, the filament is of tungsten and the anode a molybdenum cylinder. As great heat is generated by the electron bombardment of the anode the cylinder has to be of an infusible metal.

A great advance was made by the invention of the metal-glass valve in which the anode is a copper thimble which forms part of the vacuum vessel. This cylinder can be water-cooled by an enclosing jacket. The connexions for the filament current and grid are sealed through a glass base welded to the copper thimble. This power of welding metal to glass was due to a discovery of Mr W. G. Housekeeper in America that a tube of copper having a sharp chisel edge could be welded by heat to a lead glass tube and would not crack off on cooling if carefully annealed. These water- or oil-cooled metal glass thermionic valves can be made in sizes to yield even 100 kilowatts output. Similar high power transmitting valves have been made with silica bulbs by the Mullard Valve Company.

A still greater power has been obtained by the construction of generating valves entirely of metal. These can be taken to pieces for replacement of the cathode, which can no longer be called a filament, for it is a rod of tungsten a quarter of an inch or so in thickness and rendered incandescent by a current of several hundred amperes. One of the largest of these all-metal dismountable valves, which had an output of some 600 kilowatts, was shown at the Faraday Memorial Exhibition at the Albert Hall in 1931 by the Metropolitan-Vickers Electrical Co., Ltd.

In this device we see a simple laboratory apparatus transformed into an engineering appliance worthy to rank with the dynamo or transformer. The development of the thermionic valve has however been conditioned by the invention of vacuum pumps of progressively increased power. Soon after the first appearance of the valve the question of creating the highest possible vacuum in it became realized.

In America there has been a repeatedly expressed opinion that my first valves were only what are now called "soft" or low vacuum valves. A reference to my patent specifications will show that I expressly stated that the vacuum must be made as high as possible; and as a matter of fact some of my early valves were exhausted by the absorbing power of charcoal cooled by liquid air, discovered by the late Sir James Dewar. But in putting an invention into commercial manufacture an inventor is limited by the means then at disposal. Since that date we have become possessed of means of making much higher vacua than was possible in 1905, such as the Gaede molecular pump, the mercury condensation pump of Irving Langmuir, and more recently the "Apiezon" oil pump which is a condensation pump employing an oil of negligible vapour pressure at ordinary temperatures worked out by Mr C. R. Burch at the Metropolitan-Vickers Electrical Co., Ltd. These mechanical and condensation pumps have to be operated continuously in the working of the all-metal dismountable valves.

Special forms of thermionic valve have been produced lately for the production of electric oscillations of extremely high frequency required for the generation of ultra-short electric waves of less than a metre in wave-length. In the manufacture of the valves with thoriated tungsten filaments, it is necessary to produce extremely high vacua. This is now obtained partly by mechanical and condensation pumps, but also by chemical methods. Every user of modern valves knows the silvery coating on the interior of the bulb. This is due to metallic magnesium volatilized in the interior of the bulb. Magnesium can combine readily when heated with oxygen and nitrogen, producing in both cases solid compounds. Hence, if a scrap of magnesium is evaporated by heat in the interior of the exhausted valve bulb, it takes

up the residual air and helps to produce an extremely high vacuum in the vessel. Such high vacuum valves are called "hard" valves.

One simple but effective invention in connexion with the valve was the four-pin collar and corresponding socket, with the pins so arranged that the valve could not be put on wrongly but the filament terminals always to the accumulator, the anode cylinder to the high tension battery and the grid to the receiving circuit. This was due to two French inventors, M. Peri and M. Biguet.

Space does not permit reference to be made to many minor improvements, nor to the ways in which, and uses for which, the thermionic valve is available.